Centrifugal Governors: The Story of a Mistake

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Abstract. In this paper we study the centrifugal governors from the BMSTU collection in Moscow. The brief description of the governors, their distinctive features and working principles are given. The article deals with the main problems of the governors and their solutions suggested in Maxwell's, Vyshnegradsky's and Chebyshev's fundamental works. Some wrong directions in the development of governor design were identified. Inoperative mechanisms, some of which can be found in the BMSTU collection, were the result of the described dead-end directions. The article also provides information about the mathematical simulation of the operation of the governors.

1 Introduction

Creating a machine, it is important to provide the required uniformity of output shaft's motion. Uneven movement is associated with change in the process of resistance forces and moving forces during the operation. These changes are caused by the periodic character of working process or external reasons. For example, in the pump the load can be significantly lower during the stage of absorption, than during the stage of injection. In the internal combustion engine the force accelerates the engine during the combustion stroke and slows it during the intake, exhaust and compression strokes. These processes result in uneven rotation, which varies with the frequency of the working cycle. Flywheels are commonly used to prevent such irregularity.

System of automatic control is required to control the speed of an output shaft for long periods of time. When we speak about steam engines, this system is a centrifugal governor. The steam engine had to provide a uniform rotation of the output shaft, which machine tools were connected to. The task of the governor is to maintain, within a narrow range around given value, the average angular velocity of steam engine when load changes, for example when machine tools and pumps are turned on/off or when the pressure varies in the boiler. The governor automatically changes the steam flow in order to restore the equilibrium between the moving and loading moments [9].

Governors built on Watt's governor principle were successfully used in industry until the middle of the XIX century. However, later the difficulties in setting up of governors, the cases of unstable operation and oscillations appeared. Why did it

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happen? Nowadays, after studying Maxwell's and Vyshnegradsky's publications on control theory [10, 11], it's easy to answer this question.

The first steam engines were low-power engines with small shaft speed. They had huge flywheels and lightweight governor elements. As the quality of movable joints was low, governor elements moved with significant friction. The strict requirements to uniformity of rotation were absent. Later it will be shown that all these aspects together ensured the steam engine with the centrifugal governor stable operation. At the end of the XIX century powerful and high-speed steam engines were created. The growth of the shaft speed has made it possible to reduce the size of flywheels. The precision of regulation became important; hence the insensitiveness and the irregularity of governor had to be decreased. Increasing of steam engines power required augmentation of desired effort for governor elements handling and this resulted in gaining of load block weight.

Several improvements were introduced to increase the sensitivity of the governor, such as more accurate manufacturing of the mechanism's parts and better lubrication of movable joints. There were also many attempts to reduce the irregularity of the governor, modifying Watt's governor original design. Engineers believed that these measures would improve the regulation, but the process went vice versa – governors lost stability. Maxwell's paper [10, 11], where he urged to create astatic governors (i.e. governors with zero coefficient of irregularity) exacerbated the issue. Solutions of many problems were found in Vyshnegradsky's works [11]. He proved that an astatic governor is inoperative and a static governor must be equipped with a damper.

2 Classification and Basic Parameters. Static Governors

There are eight models of centrifugal governors in the BMSTU collection of mechanisms. These models of various designers and manufacturers clearly illustrate different stages of development in centrifugal governor's theory. First of all, let's consider the common classification of the governors. They are divided into three groups, such as static, astatic and pseudoastatic [17, 18].

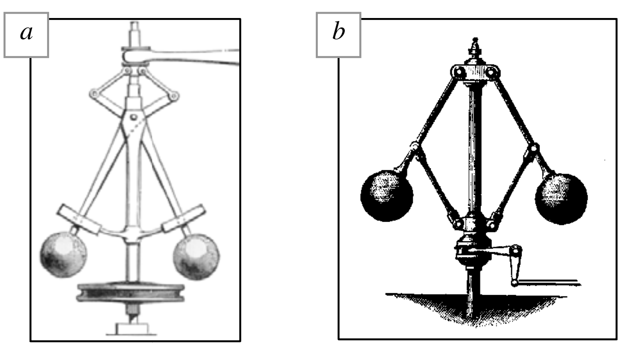

Fig. 1. a - Watt's centrifugal governor, b – modified Watt's centrifugal governor.

Static governors are governors, where each value of the shaft speed corresponds to a certain position of its sleeve, and, consequently, a certain position of throttle valve, which controls the steam flow. Watt's governor is static one. A steam engine equipped with the Watt's mechanism can't run at any speed with given load. It means that every value of the load corresponds to certain value of the speed.

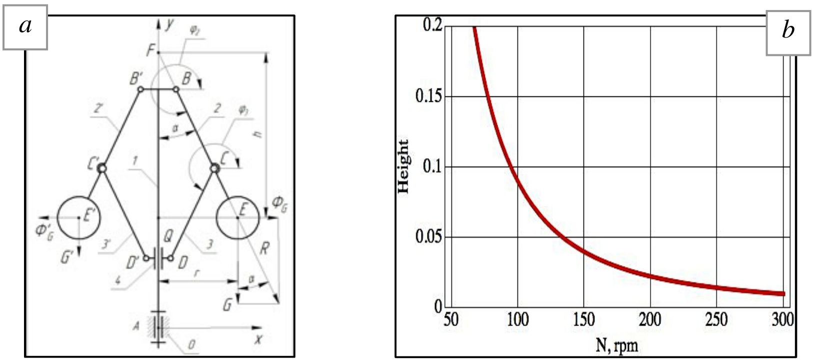

Fig. 2. a - modified Watt's centrifugal governor's force diagram, b – its theoretical characteristic.

In figure 1a the original design of Watt's governor is shown. However, the modified more compact Watt's governor was used in practice instead of the original design (Fig. 1b). Let's consider the modified mechanism. In figure 2a: 1 - the shaft of the governor 2 and 2' - levers with loads, 3 and 3'- levers, connected to the sleeve, and 4 – the sleeve. The shaft 1 is connected to the shaft of the engine and rotates with speed ω_1. Balls are in equilibrium under the inertia force Φ_G and the gravity G when the speed is constant. With the speed increasing, the equilibrium is disturbed because the inertia force Φ_G varies and the weight remains unchanged. Governor is symmetrical, so it suffices to consider a force diagram only for one half of the mechanism. Friction in the joints, the weight of the levers and the sleeve are neglected [15, 17]. The loads will be in equilibrium, if the projections of forces Φ_G and G onto an axis are equal (Eq. 1).

$$\frac{m\omega^2 \cdot r}{\sin\alpha} = \frac{m \cdot g}{\cos\alpha}, \tag{1}$$

from which it comes out

$$\omega^2 = \frac{g}{h} = \frac{g}{l_{EF} \cdot \cos\alpha}, \tag{2}$$

here m – the mass of the load, r – the distance between the load's center of gravity and rotation axis, $h = l_{EF} \cdot \cos\alpha$ – the subnormal (the projection of the normal to the trajectory from the point F onto y-axis, it's shown in figure 4a). In equation 2 l_{EF} and

g are constants, each value of the speed ω corresponds to the value of the angle α and subnormal, the growth of the speed ω increases the angle α and decreases the length of subnormal. Equation 3 defines the known relation between angular speed and rotation frequency.

$$\omega = \frac{2\pi}{60} \cdot N, \tag{3}$$

here N is the number of rotations per minute. The graph of the relation between position of the sleeve h and rotation frequency N is shown in figure 2b. This graph shows that the governor is not suitable for powerful steam engines. The curve of the relation is almost horizontal at speed values after 250 rpm that means there isn't any sleeve movement; hence there is no regulation. At the same time speed continues to grow, it can lead to accidents. Despite these shortcomings modified Watt's governor was widely used and successfully worked in low-powered steam engines.

To understand the common problems of the governors, as well as design features of various mechanisms, we will use the concepts of the irregularity and the insensitiveness of the governor. We assume that the shaft of the engine rotates with a constant speed ω_0, and the governor is in equilibrium. Let the speed of the engine has increased. Resistance forces and friction forces must be overcome when governor moves into new position. The sleeve will begin to rise only when the centrifugal force can balance the weight of the loads and resistance forces. Let's assume that this will happen at the speed of $\omega_1>\omega_0$. Similarly, the sleeve will begin to descend only when the speed is reduced to a certain value of $\omega_2<\omega_0$. When the speed varies within range from ω_2 to ω_1 the governor keeps its configuration of the levers corresponding to the speed ω_0. Therefore, the governor is insensitive within this speed range. To quantify the insensitivity of the governor, coefficient of the insensitiveness ε is used (Eq. 4); its optimum value is withhin range from 0.03 to 0.05 [17, 18].

$$\varepsilon = \frac{\omega_1 - \omega_2}{\omega_0}. \tag{4}$$

The governor is designed to maintain an average speed of engine shaft within a certain range of its change. Top position of the sleeve corresponds to the maximum speed ω_T; bottom position does to the minimum speed ω_B. Governor will be in equilibrium at all values of the speed from ω_B to ω_T. However, the equilibrium speed will be different from the controlled value ω_0. The difference between new equilibrium speed and ω_0 is an error of regulation. The coefficient of irregularity is the ratio of maximum change in speed to its mean (Eq. 5).

$$\Delta = \frac{\omega_T - \omega_B}{\omega_0}. \tag{5}$$

For astatic governor $\omega_B = \omega_T$, that means Δ equals zero. According to this, the less coefficient of irregularity is, the closer the governor is to astatism. The optimum value of Δ is 0.06, i.e. the speed fluctuation is six percent [17, 18]. Astatic governors are also called isochronous. Such name is explained by the fact that the revolution time of

governor around its axis is the same for any position of the loads; the governor has only one equilibrium speed [9].

The first problems arose when the powerful steam engines appeared. Heavy sleeve was added to the Watt's governor, for proper work with high-speed steam engines. That governor was patented in 1858 by American engineer Charles T. Porter of New York (Fig. 3). As one can see in Fig. 3a that loads are at the intersection of the upper and lower levers [2, 12, 18].

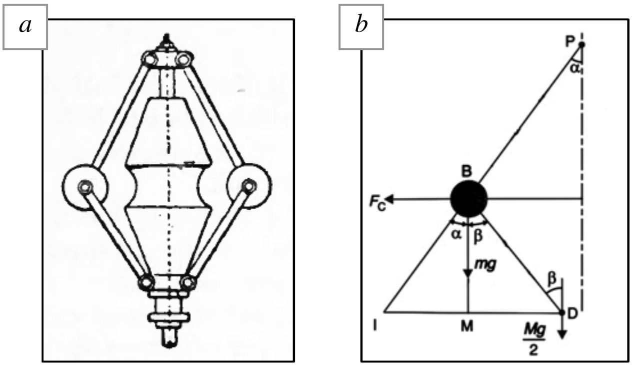

Fig. 3. a - Porter's centrifugal governor, b – its force diagram.

Porter significantly reduced the weight of the balls, thus it increased the sensitivity of the governor. Heavy sleeve was at the governor axis of rotation and its moment of inertia did not affect sensitivity. The weight of the sleeve adjusted the value of the equilibrium speed. Let's define the equilibrium speed of the governor. We take moments about the point I (Eq. 6).

$$F_C \cdot BM - mg \cdot IM - \frac{Mg}{2} \cdot ID = 0, \qquad (6)$$

here m – the mass of the load, M – the mass of the sleeve, F_C – the inertia force. Let's express the length of the moment arms in terms of tangent and introduce the ratio K (Eq. 7,8)

$$F_C = mg \cdot \tan\alpha + \frac{Mg}{2} \cdot (\tan\alpha + \tan\beta), \qquad (7)$$

$$K = \frac{\tan\beta}{\tan\alpha}, \qquad (8)$$

from which it comes out

$$\omega^2 = \frac{g}{h} \cdot \left(1 + \frac{M}{2 \cdot m} \cdot (1 + K)\right). \qquad (9)$$

Equation 9 defines the equilibrium speed of Porter's governor.

3 Astatic Governors

As mentioned above, by the middle of XIX century static governors constructed according to Watt's type of governor no longer managed with the task.

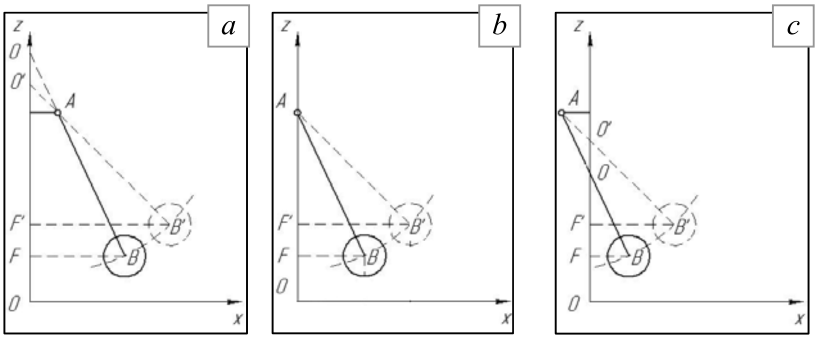

Fig. 4. Lever's layout.

The requirement for more precise regulation, arisen with the appearance of powerful steam engines, has made engineers invent new methods for reducing the insensitiveness and the irregularity. Before early research papers on the control theory appeared, irregularity and high insensitiveness had been considered to be the key problems of the governors. Watt's governor had a significant value of the coefficient of irregularity. It was attractive to reduce it in order to create more precise governor. That's why engineers created many new designs of governors, which were different from Watt's one. The simplest way to decrease the irregularity is the crisscross mounting of the upper levers (Fig 4). Equation 2 defines the equilibrium speed of Watt's governor, where h - subnormal (in our case, the distance between projection of the gravity center of the ball onto rotation axis and the point where the lever intersects with this axis - segment OF). The more h changes, the more the speed varies. Hence, the way of suspension of balls showed in figure 4c is the best and can minimize the speed fluctuations. But this is not enough to get totally astatic governor.

The main way to achieve isochronism was the creation of the governor with a parabolic trajectory of loads. Let's consider the equation of a parabola (Eq. 10)

$$x^2 = 2 \cdot p \cdot y, \tag{10}$$

here p – the subnormal of a parabola, which is constant at any point of the curve, i.e. at any position of the balls. The value of the subnormal determines value of the equilibrium speed. Equation 11 defines the equilibrium speed of the governor if the loads move along parabolic trajectory.

$$\omega^2 = \frac{g}{p}. \tag{11}$$

Fig. 5. Garnett's centrifugal governor and its sketch.

Since g and p are constants in this equation, then at any point of parabolic trajectory the only one equilibrium speed ω is possible.

There are several different designs of parabolic governors. Let's note Garnett's governor, which is kept in the BMSTU collection (Fig. 5). Here the loads are attached to the rigid guide frame, which provides a parabolic trajectory of their movement [4, 17].

Let's consider a couple of unusual governors, which were created to overcome the shortcomings of Watt's governor. The first governor was designed by German engineer F. Redtenbacher [14, 16]. The student of Moscow Craft School (MCS) P. Ivanov manufactured the model of this governor in 1862 [5]. Redtenbacher offered a completely different design, where the balls were replaced with a massive ring (Fig. 6). There is a groove in the upper part of the ring at the arc of approximately 160 degrees; this lightens one side of the ring. The ring is fixed so that it controls the movement of the sleeve through the levers, which, in turn, affects the position of throttle valve. Redtenbaher supposed to create a sensitive governor without an error of regulation. But in his works, he wrote that current model did not realize this idea [16].

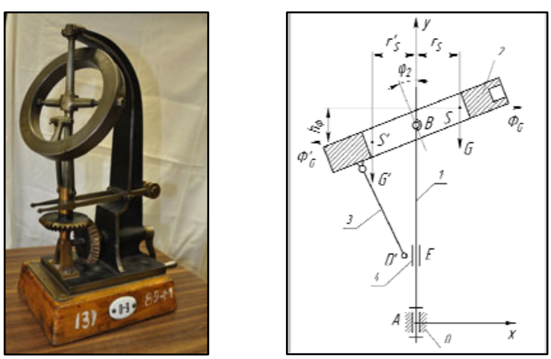

Fig. 6. Redtenbacher's centrifugal governor annd its force diagram.

Next governor was designed by F. Jenkin. Here the heavy sleeve is designed in the form of a cover, the inner part of which serves as the guidepath for divergent loads (Fig. 7). The operating principle of the governor is that the centrifugal element revolves around the main axis and is always kept at a constant angle, as the loads slide on the inner surface of the cover, which is set freely on this axis. The pressure on the sleeve always depends on speed. The disadvantage of the governor is that the equilibrium speed depends to some extent on the coefficient of friction between two surfaces.

Many different governors had been described and created until Chebyshev showed that it was possible to construct governor with the coefficient of irregularity any arbitrarily close to zero just considering Watt's original governor design by means of simple fracture of levers.

Fig. 7. Jenkins's centrifugal governor and its force diagram.

As a starting point Chebyshev took the governor with bended and intersecting levers [1, 3]. Using the principle of virtual displacements, he got an expression, which defined the squared ratio of the equilibrium speed ω to the variable speed ω_0 (Eq. 12).

$$\frac{\omega^2}{\omega_0^2} = \frac{\left[1 + \frac{\cos(\varphi+\alpha)}{\sqrt{m^2 - sin^2(\varphi+\alpha)}}\right]\cdot\sin(\varphi+\alpha) - A\cdot\sin(\psi-\varphi-\alpha)}{B\cdot\sin\ 2(\psi-\varphi-\alpha)}, \quad (12)$$

here ψ – the angle of lever's inflection, φ – the angle between levers and axis at equilibrium speed ω_0, when speed ω changes, the angle will change by a certain value α, m- the length of the upper levers. Coefficients A and B were introduced to simplify the expression (Eq. 13).

$$A = \frac{2r}{P},\ B = \frac{\omega_0^2 \cdot r^2}{P \cdot g}, \quad (13)$$

here P – the weight of the sleeve taken as a unit relative to the weight of the load, r – the length of the levers from the point of attachment to the axis to the center of the loads, the length of the levers from the point of attachment to the upper arms to the levers' inflection is also taken as a unit. It's obvious that if $\alpha = 0$ the ratio of angular speeds must be equal to one. Astatic governor has only one equilibrium speed at any possible position of the sleeve and, hence, at any possible value of angle α, i.e. equation 11 must be equal to one. Using a power series expansion and equating to zero all coefficients of the first five powers we can get a system of equations, by solving which we determine the optimal values of parameters A, B, m, φ, ψ. This set of parameters allows to reduce the speed fluctuations down to 0.1%.

Depending on the desired equilibrium speed, levers' radiuses of curvature were determined. Let's note that in contrast to conventional methods of designing centrifugal governors, Chebyshev didn't neglect the mass of levers. He designed levers of complex shape with variable width and radius of curvature. For example, in figure 10 the governor, where the regulating mass is concentrated not only in the loads themselves but also in the heavy parts of levers, is shown. Chebyshev's design governors were manufactured in IMTS (Imperial Moscow Technical School) workshops (Fig. 8, 9).

In practice, astatic governors had serious problems. While operating, the governor performed, in fact, oscillatory motion, and skipped all the time the equilibrium speed, that was totally unacceptable. What's more, there was also a problem of governor stability. Working near the resonance frequencies, the governor "went crazy" - the amplitude of the sleeve increased indefinitely. Nineteenth century engineers called this unstable behavior "hunting" and devoted much effort to improve the design of the governors. For example, the French physicist J. B. L. Foucault believed that instability could be avoided by decreasing backlash in the gears, sag in driving belts, etc. [2]. In 1871, English engineer, J. Head wrote that the solution of this problem was the usage of air damper [6].

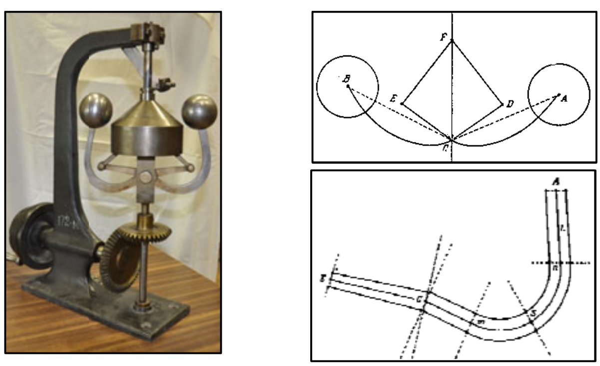

Fig. 8. Chebyshev centrifugal governor with heavy sleeve and its sketches.

Two fundamental works on the control theory of that time will be considered to realize stability and generation of oscillations problems in details. In Maxwell's article [10, 11] (published in 1868) he attempted to formulate the basic principles of different governor types. Maxwell tried to draw attention of engineers to astatic governors phenomenon. They, as Maxwell, thought were capable of more precise regulating, than static ones.

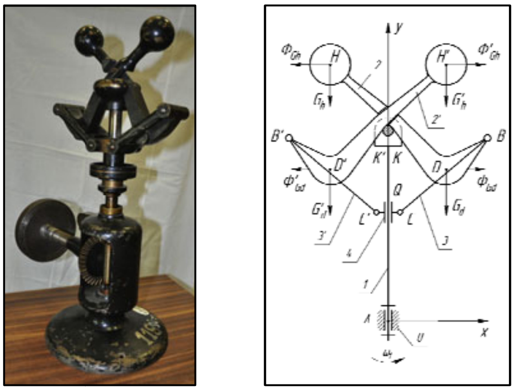

Fig. 9. Chebyshev's centrifugal governor with curved heavy levers and its force diagram.

This explains lots of different designs of astatic governors. Being involved in use of governors in astronomical instruments he didn't realize what parameters, in industry, defined the stability of governors in industry and what the relative values of certain constants in the equations of motion for steam engines were. Maxwell determined the range of parameters within which the stable operation of astatic governor was possible. But he didn't notice that this range of parameters had no practical significance for the ordinary steam engine. So this paper didn't conatain practical advice on governor design.

The origine of control theory of machines in industrial practice began in 1876 when Vyshnegradsky published his article [11]. Only by comparing the works of Maxwell and Vyshnegradsky, we can realize Vyshnegradsky's impact. He solved the equations of motion for Watt's governor and proved that astatic governors were unsuitable, essentially using the same equations that Maxwell had used to make the conclusions about the suitability of astatic governors. Vyshnegradsky got the mathematical condition of absence of self-actuation of the governor, which allowed him to make two basic theses. The first thesis is that the governor can't operate normally with a zero coefficient of irregularity, that is astatic governors aren't suitable. The closer governors to the astatism, the less is the range of parameters within which the transition process is monotone and if the coefficient of irregularity is small enough, then the oscillations of the angular speed during the transition process are inevitable. While operating, astatic governor will perform an oscillatory motion. This Vyshnegradsky's thesis is in conflict with Maxwell's intention to use astatic governors. The second thesis is that any governor, except astatic one, in order to

operate properly should have a special device generating a viscous friction (damper) [13]. Astatic governors aren't suitable even with these devices.

After Vyshnegradsky's works engineers started to understand how any changes of design parameters affect the stability of the governor. Whereas before these works no one of the engineers could have guaranteed that that governor created by him would operate properly, because of complete misunderstanding of how design features affected the stability.

4 Pseudoastatic Governors

As a result, in actual practice successful governors were those with abidance of balance between value of the coefficient of irregularity, required for stable operation of governor and for small speed fluctuations. These governors were called pseudoastatic governors.

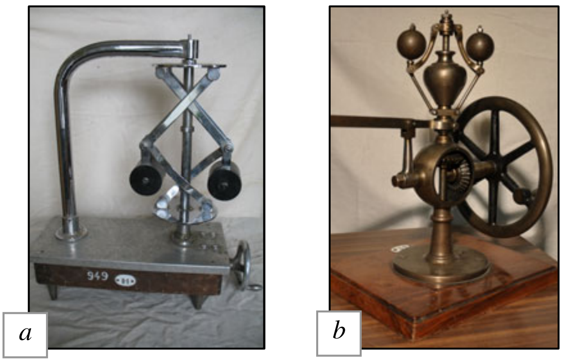

Fig. 10. a - Kley's centrifugal governor, b - Proell's centrifugal governor.

Let's consider Kley's model of governor from the BMSTU collection (Fig 10a). Contrary to certain opinions, this governor is pseudoastatic [7]. Since the exact definition of pseudoastatic governors doesn't exist then, for a rough estimate we assume that pseudoastatic governor has the coefficient of irregularity $\Delta \leq 0.04$ [15, 17]. The crisscrossed levers decrease the coefficient of irregularity. However, that design requires high height of the construction, so the shortcoming of this model is its large size.

Proll's governor (Fig. 10b) is a successful modification of Kley's governor, providing the same small speed variations at twice smaller sizes. The upper lever arms are bent, in order to allow the free movement of the loads; the sleeve is heavy and has a pear-shaped form. Let's notice that unlike the classic design, here the loads are attached to the lower levers and directed upward [4, 8]. A few designs of Proll's governor are known to exist (Fig.11a,b). One of them is kept in the BMSTU collection. Let's determine the equilibrium speed of Proll's governor rotation and plot a graph of governor's working characteristic.

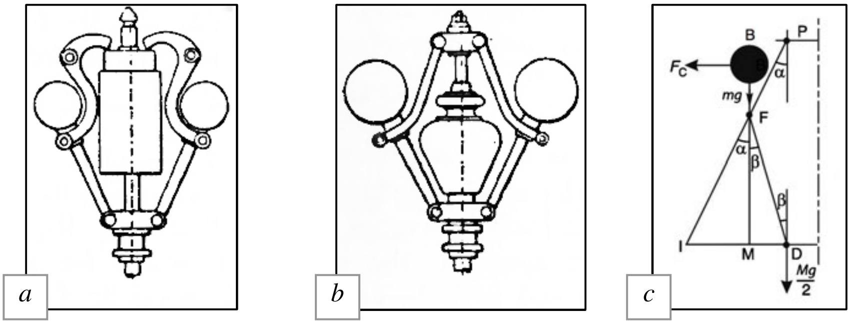

Fig. 11. a, b – sketches of different Proll's governors, c – its force diagram.

The expression for equilibrium speed (Eq. 14) differs from equation 9 by the ratio of the height of the point where lower and upper levers are intersected (segment FM) to the height of the loads' attachment (segment BM). This ratio is variable, thereby reducing the equilibrium speed fluctuations.

$$\omega^2 = \frac{g}{h} \cdot \left(1 + \frac{M}{2 \cdot m} \cdot (1 + K)\right) \frac{FM}{BM}. \tag{14}$$

The graph in figure 12 shows working characteristics of three governor types: static, astatic and pseudoastatic. Obviously, the characteristic of astatic governor is a vertical line that corresponds to the absence of equilibrium speed fluctuations. The curve of smaller slope corresponds to pseudoastatic governor that allows slight variations of the equilibrium speed. The curve of the bigger slope describes the work of static governor, which is characterized by the largest equilibrium speed fluctuations.

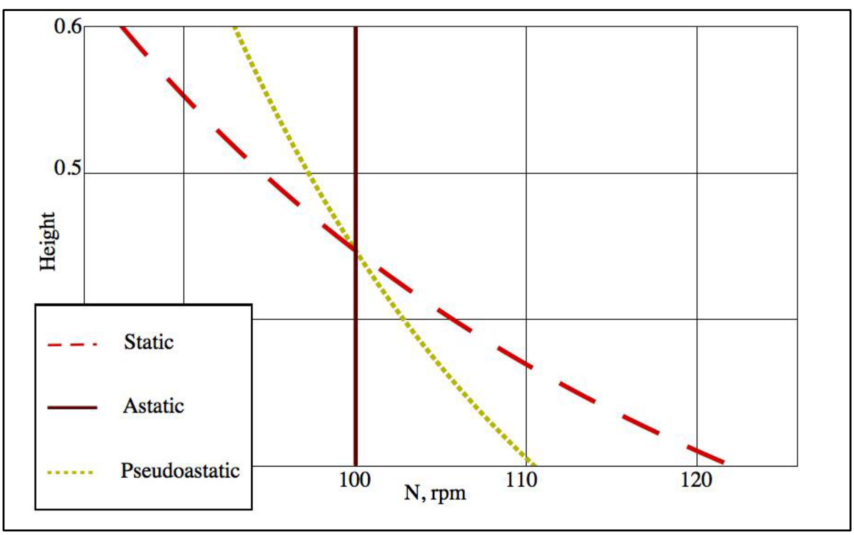

Fig. 12. Theoretical characteristics of static, astatic and pseudoastatic governors.

In the end, let's notice that the search of ideal governor has not been stopped. After pseudoastatic gravity-controlled governors engineers have started creating pseudoastatic spring-controlled governors. In these governors springs were used to react against the centrifugal force. They could be designed to operate at high speeds and were comparatively smaller in size, because there was no need in heavy sleeve and loads. Their equilibrium speed could be adjusted by changing the initial spring compression. These governors were very suitable for internal combustion engines. Among spring controlled centrifugal governors Hartnell's and Hartung's ones were the most commonly used.

5 Conclusions

Attribution is one of the main tasks of the history of technology; it answers such important questions as time of mechanism creation and inventorship. An important part of this work is to analyze causes that have led to creating and development of mechanisms. Lots of different governor designs [7] show that previous models haven't met the increasing demands. Attempt to eliminate the shortcomings of static governors with the help of astatic governors was a mistake. New models of astatic governors were unstable and failed to operate properly. However, astatic governors helped to identify the reasons of unstable behavior. They became the foundation for the development of pseudoastatic governors, which proved to be efficient in conditions of high-speed steam engines. Theoretical researches of centrifugal governors laid the foundations of the control theory. This article also provides information on mathematical simulation of basic governor types. These studies have confirmed the advantage of pseudoastatic governors over others. Simulation was based on fundamental works on the theory of governors, gathered in the lectures of IMTS professors [15, 17, 18]. Centrifugal governors are milestone in the history of technology. The governors from the BMSTU collection were officially recognized as monuments of science and technology. Even nowadays they are widely used in engineering education. For example, German firm GUNT (www.gunt.de) produces equipment for laboratory works. This equipment allows future engineers to determine working characteristics of basic governor types experimentally.

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References

1. Artobolevsky, I.I., Levitsky, N.I.: Mechanisms of P.L. Chebyshev. A Collection of scientific Heritage of P.L. Chebyshev. USSR Academy of Science (1945)
2. Bennett, S.: A History of Control Engineering 1800–1930. Institution of Electrical Engineers, London and Peter Peregrinus Ltd., Stevenage, UK (1979)
3. Chebyshev, P.L.: Complete Set of Works. USSR Academy of Science (1946)

4. Gardner, D., Hiscox, M.E.: Mechanical Movements. Powers and Devices, The Norman W. Henley Publishing Co., NY (1907)
5. Golovin, A., Tarabarin, V.: Russian Models from the Mechanisms Collection of Bauman University. Springer, Heidelberg (2008)
6. Head, J.: On a simple construction of steam engine governor having a close approximation to perfect action. Proceedings of the Institution of Mechanical Engineers 22, 213–228 (1871)
7. Header, H.: A Handbook on the Steam Engine. Crosby Lockwood and Son, London (1902)
8. Hopkins, A.A., Bond, A.R.: Scientific American Reference Book. MUNN & Co., NY (1914)
9. Manychkin, N., Sakharov, M., Tarabarin, V.: The Models of Centrifugal Governors in the Collection of BMSTU. In: Proceedings of EUCOMES 2010, pp. 511–518. Springer, Heidelberg (2010)
10. Maxwell, J.C.: On Governors. Proceedings of the Royal Society of London 16, 270–283 (1868)
11. Maxwell, J.C., Vyshnegradsky, I.A., Stodola, A.: Theory of automatic regulation. USSR Academy of Science (1949)
12. Mayr, O.: The Origins of Feedback Control, English edn. MIT Press, Cambridge (1970)
13. Merkin, D.R.: Introduction to the Theory of Stability of Motion. Science (1976)
14. Moon, F.C.: The Machines of Leonardo da Vinci and Franz Reuleaux. Springer (2007)
15. Orlov, F.E.: Steam Engines. Lections of prof. Orlov. IMTS (1890)
16. Redtenbacher, F.: Die Bewegungs-Mechanismen. F. Bassermann, Heidelberg (1866)
17. Zernov, D.S.: The Building of Steam Engines. Lections of prof. Zernov. IMTS (1895)
18. Zernov, D.S.: Theory of Steam Engines. IMTS (1896)